OUTLINE OF THE PROPOSED TOPIC OF RESEARCH

Name of Candidate : Er. Kapender Singh Phogat

ID NO. : 2011PhDENGG002

Place of Research Work and Organization : IET, JK Lakshmipat University, Jaipur

Guide : Dr. B V Babu

Qualification : PhD

Designation : Director - IET

Organization : JK Lakshmipat University, Jaipur

1. **Proposed Topic of Research:**
   Optimal Design and Synthesis of Heat Exchanger Networks

2. **Objectives of the Proposed Research:**
   1. To find out optimal Heat Exchanger Network (HEN) using evolutionary computation techniques based on population based search algorithms such as Genetic Algorithm, Differential Evolution, etc.
   2. To compare the obtained results of HENs with the existing HEN in a refinery industry.
   3. To develop a mathematical model to evaluate the optimum numbers of tanks and their temperature levels when excess heat is released from a hot and warm fluid/oil system.
   4. To propose measures to improve energy efficiency at the plant and to conduct a simplified economic evaluation of the proposed measures.

3. **Background of the Proposed Research**

   3.1 Introduction

   Global warming caused by emission of greenhouse gases such as carbon dioxide (CO_2) is an environmental issue frequently discussed today. Resulting policies provide clear incentive for industry to reduce fossil fuel consumption and consequently avoid emissions leading to climate change.

In a global context, it is essential to reduce the fossil-based energy consumption in order to decrease the environmental impact of human activities. Industry's share of the total energy consumption is very large, and thus reduction of energy use is highly motivated in this sector.

The two problems of diminishing supplies of fossil fuels and increased CO_2 levels motivate research and development towards a sustainable energy system with less use of fossil fuels. To decrease this use, two main paths must be pursued:

- Development and introduction of new energy production techniques, not relying on fossil fuels.
- Energy conservation (intensification) measures to use fuels more effectively.

Energy efficiency is one of many ways to reduce the problems of releasing more greenhouse gases into the atmosphere. The potential for energy savings due to energy efficiency measures can be large in industrial processes, especially in energy intensive businesses such as the refinery industry. Increases in energy efficiency will decrease the need for firing fossil fuel to provide heat for industrial plants and consequently CO_2 emissions will also decrease. Hence, the climate change issue together with a concern about depletion of fossil fuel reserves provides incentive to investigate energy efficiency.

Increased energy efficiency also provides economic benefits since reduced utility usage implies reduced fuel costs. The price of fossil fuels is rising and is predicted to continue to rise, which further motivates a reduced fuel usage. Taxes and other costs associated with CO_2 emissions are also expected to increase as policies to curb global warming are implemented.

A number of different options are possible to reduce industrial energy use. Proposed measures include e.g. heat pumping, combined heat and power generation, fuel switching, more efficient unit operations, and increased heat recovery by heat exchange.

3.2 Literature Review

3.2.1 The field of Process Integration, past and present:

The definition of Process Integration was first established within the International Energy Agency (IEA) in 1993 as:

"Systematic and General Methods for Designing Integrated Production Systems, ranging from Individual Processes to Total Sites, with special emphasis on the Efficient Use of Energy and reducing Environmental Effects."

This definition has later been reformulated:

"Process Integration is the common term used for the application of methodologies developed for System-oriented and integrated approaches to industrial process plant design for both new and retrofit applications.

Such methodologies can be mathematical, thermodynamic and economic models, methods and techniques. Examples of these methods include: Artificial Intelligence (AI), Hierarchical Analysis, Pinch Analysis and Mathematical Programming.

Process Integration refers to Optimal Design; examples of aspects are: capital investment, energy efficiency, emissions, operability, flexibility, controllability, safety and yields. Process Integration also refers to some aspects of operation and maintenance."
This reformulation bears witness to the evolution of process integration that has taken place during the last fifteen years. Today, synthesis and design of mass exchange networks (MEN) [1, 2], distillation column integration and control [3], and property integration [4] are good examples of the breadth that Process Integration has acquired.

Other important aspects are the designs of the reactor system, separation system, and control system. Linnhoff [5] represented the hierarchy of a chemical process synthesis with the "onion diagram", which starts with the design of the reactor system, continues with the separation system and finishes with the construction of the heat exchanger network. The "onion diagram" has later been expanded to include utility and power generation systems and the important coupling to society [6]. With the development of computer calculation capacity (CCC), Dhole [7] argued that simultaneous optimization strategies could be used to minimize the total annual cost of the plant.

In the following presentation of important literature in the field of Process Integration, only Heat Exchanger Network (HEN) synthesis and design and related issues are reviewed.

3.2.2 HEN Synthesis:

Heat exchanger network synthesis was first systematically studied in the 1960s. Work by Westbrook [8] and Hwa [9], who created the superstructure based on mathematical programming, and Masso and Rudd [10], who used heuristic rules to design the network, were among the pioneers. As the methods developed, two main algorithms for match selection were being used, referred to by Nishida et al. [11] as simultaneous algorithms and sequential algorithms.

Kesler and Parker [12] suggested the assignment problem in linear programming, based on a simultaneous algorithm. Each stream in the network is divided into equally small sub streams with a certain heat load. Hot sub streams are then assigned to cold sub

streams while the sum of the costs associated with each assignment is minimized. Further evolution is then required to create a practical network of all the assigned sub streams. Tree-searching methods and decomposition methods are examples of sequential algorithms. Pho and Lapidus [13] suggested a tree-searching method that developed the entire tree, but only systems with less than 10 streams could be solved. In order to increase the number of streams and thereby the problem size, the methods were combined with heuristic or bounding methods. One example of a heuristic method is the approach presented by Ponton and Donaldson [14] who suggested that the hot stream with the highest supply temperature should be matched with the coldest stream with the highest target temperature.

Three fundamental concepts in heat exchanger network synthesis were discovered in the 1970s, two of them introduced by Hohmann [15]. He presented the first rigorous way of establishing the minimum utility usage prior to design. He also suggested the (N-1) rule for the minimum number of units in the design, where N is the number of streams. These two results were systematized and evolved by Linnhoff et al. [16]. The third discovery, and a milestone in heat exchanger network synthesis, was the identification of the heat recovery pinch as a bottleneck for further heat integration, independently discovered by Umeda et al. [17] and Linnhoff et al. [16].

This literature survey will therefore start with a presentation of the most important development of heat exchanger network synthesis in grass-root situations. A number of review papers have been published to cover process synthesis, such as Hendry et al. [18], Nishida et al. [11] and, in heat exchanger network synthesis, Gundersen [19], Linnhoff [20], Jezowski [21] and Fuhrman [22].

3.2.3 Grass – root HEN Design:

Today two main approaches in heat exchanger network synthesis dominate: the Pinch Analysis (Pinch Technology or Pinch Design Method) and mathematical programming methods. In addition, there are methods employing heuristic and knowledge-based systems. This classification is rather rough, since all the methods contain common elements such as basic thermodynamics. The Pinch Analysis and mathematical methods are discussed below.

3.2.3.1 Pinch Analysis:

The discovery of the heat recovery pinch led to development of a whole new methodology for process synthesis, called pinch technology. Apart from its usefulness in heat exchanger network synthesis, it has been applied to study the effects on a process

when new equipment is introduced. I will mention briefly some of these publications: Kemp [23] on separation systems, Wallin et al. [24] on heat pumps, and Strömberg and Berntsson [25] on combined heat and power.

Linnhoff and co-workers are the most important contributors to the development of the pinch design method. Linnhoff et al. [16] provide the fundamental understanding of the basic concepts involved in heat exchanger network design. They explain the relation between ΔTmin and energy recovery, using the composite curves introduced by Huang and Elshout [26]. They discuss loops and extend the (N-1) rule for minimum number of units suggested by Hohmann [15], by applying Euler's theorem to the network problem. Their result (N+L-S) accounts for the number of loops (L) and subsystems (S) in the network.

Linnhoff and Hindmarsh [5] presented the pinch design method for heat exchanger networks. The approach behind this method is the recognition of the pinch point as the most constrained region of a design. Therefore, the problem is split at the pinch point into two separate systems, above and below the pinch point. The design of the network starts in the most constrained region of each system, located immediately above or below the pinch point. Sets of rules or feasibility criteria are applied to these streams to decide which ones are to be matched. The feasibility criterion is derived from the FCp relation between the two streams considered for a match. In order to achieve the minimum number of units in the network, the tick-off heuristic is applied, which states that at least one of the streams considered for a match must be satisfied. Further away from the pinch, these rules are not applied and are left to the designer's own judgment. The remaining problem analysis is also described and recommended for use in more complex situations of the design stage.

The approaches to calculate maximum energy recovery and minimum number of units at different ΔTmin values made it possible for design engineers to distinguish between good and bad network structures prior to design. Targeting for minimum heat exchanger area was discussed by Nishida et al. [27] in relation to the heat content diagram and by Nishida et al. [11] in relation to the composite curves. Their approach was based on equal heat transfer coefficients between all matches in the network, and on vertical counter-current heat transfer between the composite curves. Townsend and Linnhoff [28] extended their work to account for individual heat transfer coefficients for the streams with the presentation of the Bath formula, based on the spaghetti network. Their formulation is only an approximation but works well in many situations.

Ahmad and Linnhoff [29] addressed the issue of cost targeting for the most economic ΔTmin prior to design. They calculated the cost of energy, the cost of minimum number

of units, and the cost of heat exchanger area at different values of ΔTmin. These costs were added and drawn in a cost-ΔTmin plot, from which the most cost-effective ΔTmin could then be selected. This targeting approach was later developed and presented as super targeting by Linnhoff and Ahmad [30]. Further refinement of the detail of the targeting procedure was the main concern in the papers presented by Ahmad and Smith [31] and by Hall et al. [32]. Ahmad and Smith [31] described a method for targeting the minimum number of shells and near-minimum area in networks requiring 1-2 heat exchangers. Hall et al. [32] developed a method which allows capital cost targets to take into account different materials of construction, pressure ratings, and heat exchanger type. This was achieved by assigning weights to the heat transfer coefficients of the Bath formula by Townsend and Linnhoff [28]. A review and update on costs for heat exchangers was later published by Taal et al. [33]. Linnhoff and Ahmad [34] used super targeting for predicting the optimal ΔTmin and then used the driving force plot by Linnhoff and Vredeveld [35] and the remaining problem analysis by Linnhoff and Hindmarsch [5] to construct the network. A concept similar to super targeting was presented by Maréchal and Kalitventzeff [36], using a combination of pinch-based techniques and mathematical programming.

The concept of the dual approach temperature, i.e. using two different temperature differences to set the limits of the network, was first introduced by Challand et al. [37] and Colbert [38]. These two temperatures are the heat recovery approach temperature (HRAT), which is used to determine the minimum utility requirements, and the exchanger minimum approach temperature (EMAT). The first attempt to develop the dual approach temperature approach into a synthesis method was made by Trivedi et al. [39, 40]. Based on these results, Wood et al. [41] developed the pseudo-pinch design method. By using two different minimum approach temperatures for the streams crossing the pinch (EMAT < HRAT), some streams are allowed totally or partially to slip across the pinch point, based on a set of heuristics. Thus a single stream can be located on one side of the pinch point and stream pairs can be arranged on the same side in a subset. Suaysompol and Wood [42] presented the flexible pinch design method, where the set of heuristics has been reduced in comparison to the pseudo-pinch design method.

Instead of specifying the heat transfer coefficients for the streams, a maximum allowable pressure drop is specified for each stream. An approximate area contribution and a heat transfer coefficient for each stream are then calculated iteratively within the area target calculation. Jegede and Polley [43] developed a procedure to optimise single heat exchangers in a network. Simple relationships were used to trade off heat exchanger area and power requirements of both streams for a given heat load. Muralikrisnhna and Shenoy [44] presented a methodology that determines the feasible region for shell-and-tube heat exchanger pressure drop by accounting for both geometrical and operating

constraints. The area target ensures an exchanger of the smallest size with minimum capital cost, whereas the cost target yields the optimum pressure drops accounting for the trade-off between power consumption and heat exchanger area.

Zhu et al. [45] proposed a heuristic method which does not rely on pinch point decomposition. Instead the composite curves are decomposed into a number of blocks. The segments of the composite curves located within each block are represented by a straight line, called quasi-composites. Area requirements for all feasible matches are calculated, based on maximum heat exchange in each block. These areas are compared with the ideal areas of the quasi-composites. A good set of matches is then selected from the whole set of possible matches of the block, taking matching constraints into consideration. Matches are selected for all blocks simultaneously. The number of enthalpy intervals used to synthesize the heat exchanger network is greatly reduced, compared with the spaghetti structure. Once the matches in each block have been selected, the total cost of the network is minimized.

Westphalen et al. [46] introduced a controllability index for HENs that can be used as a complement to design methods and also be used to identify trade-offs between controllability and heat integration.

3.2.3.2 Mathematical Programming:

The ideal way of finding the optimum solution to a heat exchanger network design with a mathematical method would be to use an objective function that consists of the annualized investment and operating costs. Unfortunately, the mathematical formulation of the problem for such an objective function is very complicated. It requires a mixed-integer non-linear program formulation, which involves non-convexities in the objective function and a rather large number of variables. Therefore, the two most important issues in mathematical methods are to find an efficient and reasonably sized representation of the problem and to use or develop efficient optimization techniques that can exploit the representation of the problem.

Mathematical methods, as well as pinch-based methods, benefited immensely from the discovery of the heat recovery pinch. It was now possible to establish the thermodynamic limit and determine the minimum hot and cold utility requirements for any process. Cerda et al. [47] presented a paper that formulated the minimum utility calculation for a heat exchanger network synthesis as a transportation problem from linear programming, a well-known problem for which efficient algorithms exist. It is possible to add non-thermodynamic constraints on matching certain streams, wholly or in part. Cerda and Westerberg [48] used the transportation problem to calculate the minimum utility

requirements. In order to find the smallest number of matches in the process, a Mixed-integer linear programming (MILP) model was relaxed into a linear programming transportation problem and solved. However, the knowledge of the smallest number of matches does not imply knowledge of the heat exchanger network structure, since stream splits and loops may be involved and the actual structure therefore needs further evolution.

A similar approach was suggested by Papoulias and Grossmann [49]. They solved the minimum utility requirement by means of the transshipment model, which is a considerably smaller variation of the transportation model. Non-thermodynamic constraints are taken into account by an extension of the transshipment model. The minimum number of matches that should take place in the network is determined by means of the transshipment model involving the solution of a MILP, by means of a branch-and-bound method. The heat exchanger network configuration is not obtained directly from the solution of the MILP transshipment model, but it contains all necessary information to derive the network by hand. Since the configuration is not obtained, several networks will sometimes have to be derived manually and analyzed in detail before a structure can be selected.

Ciric and Floudas [50] also suggested an approach, without decomposition, to simultaneously solve the utility consumption levels, the process stream matches, and the network configuration. Their approach is based on the hyper structure of Floudas and Ciric [51] and a modified transshipment model to select heat loads. The problem is formulated as a MINLP problem.

Briones and Kokossis [52] developed an area targeting method that replaced the transshipment problem in the hyper targets approach. This eliminated the risk of ending up in inferior points in the optimization.

In 2003, Mitzutani et al. [53] proposed an optimization model that incorporated detailed heat exchanger design into the network optimization problem. This model did not include piping considerations.

Zhu et al. [54] automated a method for block decomposition before NLP optimization, the blocks containing streams with similar characteristics.

Daichendt and Grossmann [55] described a screening procedure for MINLP formulation to overcome the computational complexities associated with binary variables. A base-case design is set as upper bound. Every solution to the aggregated model whose cost is greater than the base cost can thus be eliminated.

Pettersson and Björk & Petterson [56, 57] presented methods that allow an increased number of streams and thus a greater problem size. The drawback with these methods is that the global optimum cannot be ensured.

Nejad et al [58] presented a method in which temperature dependency of streams' physical properties have significant effects on HENs design. They suggested that an average value can be utilized during each temperature interval in order to determine the physical properties of the streams. The results demonstrated by them shows that when splitting streams into two or more segments within the existing plant, the pinch point increases by about 3 ^{o}C, and hot and cold utilities consumption increases by approximately 23% and 11% respectively.

3.2.3.3 Other Methods:

Different forms of evolutionary search approaches have been developed recently for HEN design problem: genetic algorithms [59, 60, 75-76], Tabu search [61], graph-theoretic principles [62] or randomization techniques [63], tree searching algorithm method [13, 75-76], neural networks [64, 75-76], mixed integer nonlinear programming [65, 66, 75-76], R-curve and Site Source Sink Profile (SSSP) analysis [67], and Differential Evolutionary approach[68, 76], etc.

4. Gaps in Existing Research:

1. HEN Design is very complex optimization problem which can't be solved using conventional optimization techniques. Literature survey suggests that evolutionary computation techniques have been successfully applied to many Non–Linear Complex problems with constraints.
2. Genetic Algorithms have been applied to some of the HENs problems.
3. Differential evolution, an improved version of genetic algorithms has been shown to solve many industrial optimization problems, which has not been reported to be applied to HENs problems.
4. There is a need to systematically apply deferential evolution and its various strategies' such as hybrid–differential evolution, improved differential evolution, trigonometric differential evolution, etc. to solve HENs problems.
5. There is a lot of scope for differential evolutionary methods to obtained optimal HENs.

5. Problem Analysis:

The study will focus on the most energy consuming part of the plant, namely the distillation area. The first step of the study is to determine how much energy could

theoretically be recovered and reused internally in the process. Establishing such energy use targets can be performed using pinch analysis. Pinch analysis can also be used to identify whereabouts in the plant there is surplus or deficit of heat.

The pinch analysis highlight where in the system the main energy flows are located. Further analysis is needed to identify where in the process improvements are needed in order to reduce energy usage. Investigation of the utility system may lead to suggestions of different energy measures. Examples of measures may be more preheating of the fuel oil before entering the furnace or preheating of the boiler feed water. The heat exchangers can be modified as well as how steam is produced.

Further, the expected surplus of process heat could be managed by delivering heat to the district heating network. Another way of dealing with the waste heat is to use it for heating the storage cisterns. Some of these different arrangements and utility systems will be further investigated and some will not, depending on how large energy gains they have.

6. Methodology

Based on the objectives set for the present study and the background work reported in literature with their limitations, the methodology of the present study is proposed as follows:

6.1 Phase 1: Literature Survey

A detailed literature survey will be carried out for finding the limitations of experimental work and mathematical models and obtaining the various heat exchanger network designs from literature for a given requirement of hot and cold utilities. Continuous literature survey will be carried out to collect the information required during various stages of the proposed research. The source of this literature survey will be various available journals like, Chemical Engineering Science, Computers and Chemical Engineering, Electronic Scientific Journal "Oil and Gas Business", Chemical Engineering Transactions, Chemical Engineering Journal, Industrial and Engineering Chemistry Research, American Institute of Chemical Engineers Journal, Journal of Chemical Technology and Biotechnology, and Chemistry and Biochemical Engineering etc., internet sites and e-journals source like Science Direct subscribed through library of MNIT or IITs.

6.2 Phase 2: Evolutionary Computation approach to obtained optimal HENs

In the second phase of the research work, we will obtain the numbers of HENs using the evolutionary computation technique and pinch analysis. Energy optimization can be

achieved along two routes; paying less per unit of energy, or reducing energy consumption per unit of product. Co-generation of heat and power is an example of the first route, whilst energy integration of the process plant is an example of the second one.

6.3 Phase 3: Data Collection

In this phase, we will collect the data for the temperature required for hot and cold utilities for a refinery industry. The data will be collected for the physical and chemical properties of each stream from an existing refinery industry. From the collected data we will be able to calculate the minimum heating and cooling requirements for HEN. The main objective of this method is to save the expenses by maximizing process to process heat recovery. And hence obtained no. of optimal design of HENs these will be significantly contributed to decrease in energy consumption and therefore energy expenses. This will accomplished by minimizing the use of utilities and maximizing heat recovery between existing hot and cold streams.

6.4 Phase 4: Analysis of Results

Analysis of evolutionary results will start after data collection from a refinery industry and will be continued to till a best optimal HEN may obtain. From the collected data, suitable/optimal HEN will be selected on the basis of minimal capital cost requirement, maximum optimization of the available energy and reducing environmental effects. Same combination will be used for further research work.

6.5 Phase 5: Mathematical Modeling

A mathematical model will be formulated on the basis of Pinch Technology and differential evolution technique. It will be a mathematical interpretation of equilibrium and kinetic data with complexation hot and cold utility required. Using the mathematical model, parametric study and sensitivity analysis will be carried out to get the effect on the performance of HEN and the optimum parameters will be found out.

6.6 Phase 6: Economic Evaluation

After the design and synthesis of HENs using differential evolution and modeling final economic evaluation of the one of the best suited HEN will be purposed. Economical evaluation will give the economic feasibility of the HEN to a refinery industry that required minimal capital cost, optimized the available energy to get the desired stream temperatures, and having minimal emission of the harmful gases like CO_2 as compared to existing HEN.

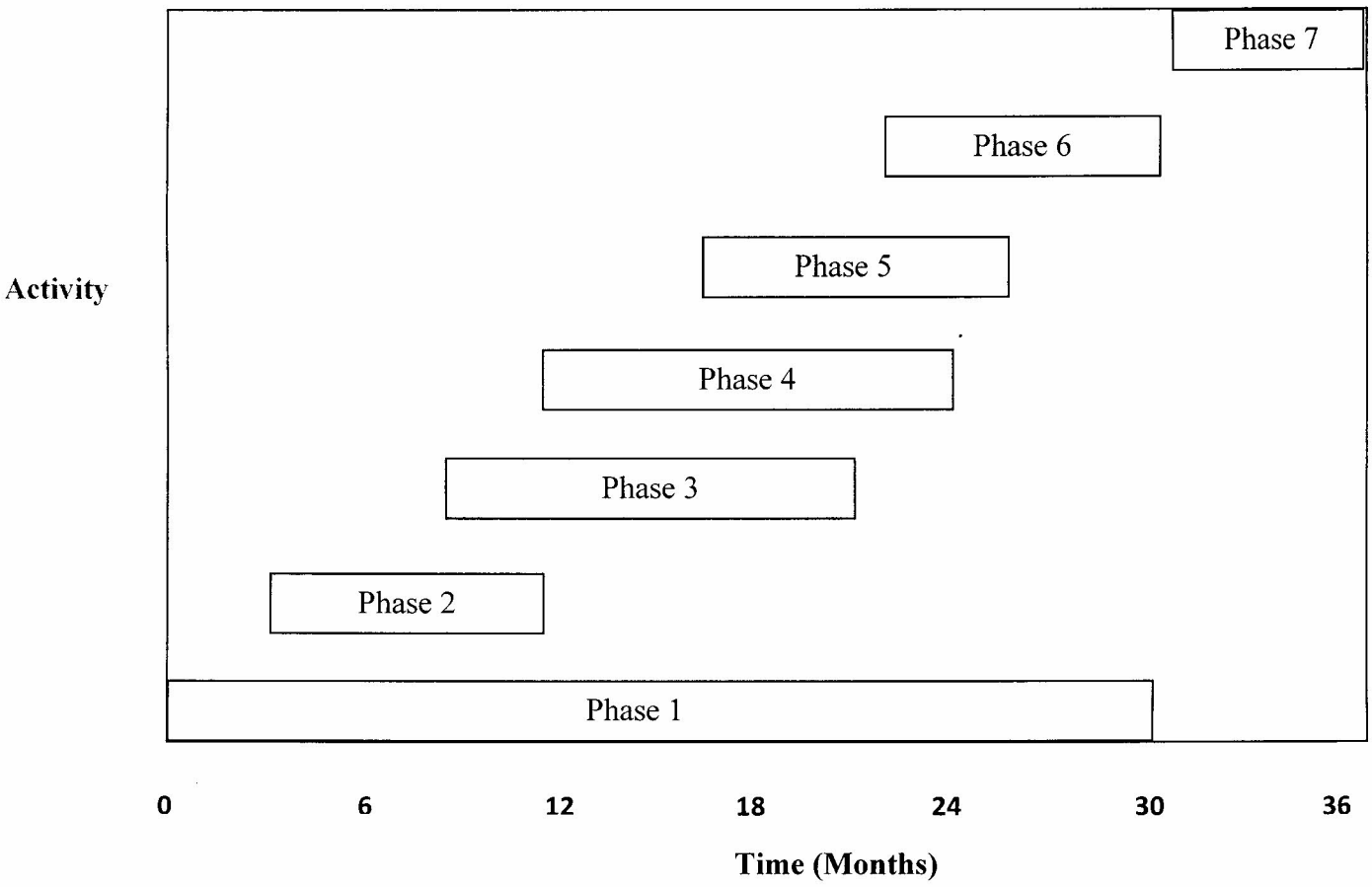
6.7 Phase 7: Conclusion and Thesis writing

In this phase, all the practical and theoretical work carried out in different phases will be documented in the form of thesis.

7 Work Plan

The work-plan for the above-mentioned seven activities is shown in figure 1.

Figure 1: WORK PLAN



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